
Interference in the 2.4 GHz ISM Band: Challenges and Solutions

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RÉSUMÉ.

ABSTRACT. Most emerging radio technologies for Wireless Personal Area Networks such as the Bluetooth protocol are designed to operate in the 2.4 GHz ISM band. Since both Bluetooth and IEEE 802.11 devices use the same frequency band and may likely come together in a laptop or may be close together at a desktop, interference may lead to significant performance degradation. The main goal of this paper is to describe the interference problem and to highlight a coexistence framework for these technologies to operate in a proximal environment. We give an overview of several coexistence solutions proposed for various interference scenarios. We study several factors that may impact interference such as fragmentation and the choice of packet encapsulation and give simulation results for selected scenarios and configurations of interest.

MOTS-CLÉS :

KEYWORDS: WPAN, Bluetooth, WLAN, Interference, Coexistence

1. Introduction

Increasingly people work and live on the move. To support this mobile lifestyle, especially as work becomes more intensely information-based, companies are producing various portable and embedded information devices including PDAs, pagers, cellular telephones and active badges. At the same time, recent advances in sensor integration and electronic miniaturization are making it possible to produce sensing devices equipped with significant processing memory and wireless communication capabilities to create smart environments where scattered sensors could coordinate to establish a communication network. These wearable computing devices and ad-hoc smart environments impose unique requirements on the communication protocol design such as low power consumption, frequent make and break connections, resource discovery and utilization and have created the need for Wireless Personal Area Networks (WPANs).

A WPAN is a wireless ad hoc data communications system that allows a number of independent devices to communicate. WPAN is distinguished from other types of wireless networks in both size and scope. Communications in WPAN are normally confined to a person or object and extend up to 10 meters in all directions.

This is in contrast to Wireless Local Area Networks (WLANs) that typically cover a moderately sized geographic area such as a single building, or campus. WLANs operate in the 100 meter range and are intended to augment rather than replace traditional wired LANs. They are often used to provide the final few feet of connectivity between the main network and the user. Users can plug into the network without having to look for a place to link their computer, or having to install expensive components and wiring.

What is emerging today are wireless technologies, including IEEE 802.11 [802], Bluetooth [GRO a], IrDa [ASS], and HomeRF [GRO b][K. 00], that promise to outfit portable and embedded devices with high bandwidth, localized wireless communication capabilities that can also reach the globally wired Internet.

Due to its almost global availability, the 2.4 GHz Industry Scientific and Medical (ISM) unlicensed band constitutes a popular frequency band suitable to low cost radio solutions such as the ones proposed for WPANs and WLANs. This sharing of the spectrum among various wireless devices that can operate in the same environment may lead to severe interference and result in significant performance degradation.

The main goal of this paper is to describe the interference problem. We give several interference scenario examples and provide a qualitative discussion of the performance degradation resulting from interference based on several published results in the literature. We also give an overview of the coexistence framework adopted by the IEEE 802.15.2 Task Group and discuss some of the coexistence solutions proposed.

The rest of the paper is structured as follows. In section 2, we give some general insights on the Bluetooth and WLAN device operation. In section 3, we describe the interference problem and give several interference scenarios as example. In section 4,

we present a coexistence framework and in section 5 give some insights on factors that might impact interference such as the use of Forward Error Correction (FEC), the choice of the packet size and encapsulation. Our observations are accompanied with simulation results obtained for an example scenario. Concluding remarks are offered in section 6.

2. Wireless Technologies in the 2.4 GHz Band

In this section we give an overview of the various radio technologies operating in the 2.4 GHz unlicensed ISM band. We focus on the Bluetooth and IEEE 802.11 protocols.

2.1. The Bluetooth Specifications

In this section, we give a brief overview of the Bluetooth technology [GRO a] and discuss the main functionality of its protocol specifications which consist of several modules, namely, the Radio Frequency (RF), Baseband (BB) and Link Manager (LM). Bluetooth is a short range (0 m - 10 m) wireless link technology aimed at replacing non-interoperable proprietary cables that connect phones, laptops, PDAs and other portable devices together. Bluetooth operates in the ISM frequency band starting at 2.402 GHz and ending at 2.483 GHz in the USA, and Europe. 79 RF channels of 1 MHz width are defined. The air interface is based on an antenna power of 1 mW (0 dBi gain). The signal is modulated using binary Gaussian Frequency Shift Keying (GFSK). The raw data rate is defined at 1 Mbits/s. A Time Division Multiplexing (TDM) technique divides the channel into 625 μ s slots. Transmission occurs in packets that occupy an odd number of slots (up to 5). Each packet is transmitted on a different hop frequency with a maximum frequency hopping rate of 1600 hops/s.

Two or more units communicating on the same channel form a piconet, where one unit operates as a master and the others (a maximum of seven active at the same time) act as slaves. A channel is defined as a unique pseudo-random frequency hopping sequence derived from the master device's 48-bit address and its Bluetooth clock value. Slaves in the piconet synchronize their timing and frequency hopping to the master upon connection establishment. In the connection mode, the master controls the access to the channel using a polling scheme where master and slave transmissions alternate. A slave packet always follows a master packet transmission.

There are two types of link connections that can be established between a master and a slave : the Synchronous Connection-Oriented (SCO), and the Asynchronous Connection-Less (ACL) link. The SCO link is a symmetric point-to-point connection between a master and a slave where the master sends an SCO packet in one TX slot at regular time intervals, defined by T_{SCO} time slots. The slave responds with an SCO packet in the next TX opportunity. T_{SCO} is set to either 2, 4 or 6 time slots for $HV1$, $HV2$, or $HV3$ packet formats respectively. All three formats of SCO packets are defi-

ned to carry 64 Kbits/s of voice traffic and are never retransmitted in case of packet loss or error. The ACL link, is an asymmetric point-to-point connection between a master and active slaves in the piconet. Several packet formats are defined for ACL, namely *DM1*, *DM2*, and *DM3* packets that occupy 1, 3, and 5 time slots respectively. An Automatic Repeat Request (ARQ) procedure is applied to ACL packets where packets are retransmitted in case of loss until a positive acknowledgement (ACK) is received at the source. The ACK is piggy-backed in the header of the returned packet where an ARQN bit is set to either 1 or 0 depending on whether the previous packet was successfully received or not. In addition, a sequence number (SEQN) bit is used in the packet header in order to provide a sequential ordering of data packets in a stream and filter out retransmissions at the destination. Forward Error Correction (FEC) is used on some SCO and ACL packets in order to correct errors and reduce the number of ACL retransmissions.

2.2. The IEEE 802.11 Specifications

The IEEE 802.11 standard [802] defines both the physical (PHY) and medium access control (MAC) layer protocols for WLANs. In this sequel, we shall be using WLAN and 802.11 interchangeably.

The IEEE 802.11 standard calls for three different PHY specifications : frequency hopping (FH) spread spectrum, direct sequence (DS) spread spectrum, and infrared (IR). The transmit power for DS and FH devices is defined at a maximum of 1 W and the receiver sensitivity is set to -80 dBmW. Antenna gain is limited to 6 dB maximum. In this work, we focus on the 802.11b specification (DS spread spectrum) since it is in the same frequency band as Bluetooth and the most commonly deployed.

The basic data rate for the DS system is 1 Mbits/s encoded with differential binary phase shift keying (DBPSK). Similarly, a 2 Mbits/s rate is provided using differential quadrature phase shift keying (DQPSK) at the same chip rate. Higher rates of 5.5 and 11 Mbits/s are also available using techniques combining quadrature phase shift keying and complementary code keying (CCK); all of these systems use 22 MHz channels. Details of the modulation methods are provided in Section III.

The IEEE 802.11 MAC layer specifications, common to all PHYs and data rates, coordinate the communication between stations and control the behavior of users who want to access the network. The Distributed Coordination Function (DCF), which describes the default MAC protocol operation, is based on a scheme known as carrier-sense, multiple access, collision avoidance (CSMA/CA). Both the MAC and PHY layers cooperate in order to implement collision avoidance procedures. The PHY layer samples the received energy over the medium transmitting data and uses a clear channel assessment (CCA) algorithm to determine if the channel is clear. This is accomplished by measuring the RF energy at the antenna and determining the strength of the received signal commonly known as RSSI, or received signal strength indicator. In addition, carrier sense can be used to determine if the channel is available. This

technique is more selective since it verifies that the signal is the same carrier type as 802.11 transmitters. A virtual carrier sense mechanism is also provided at the MAC layer. It uses the request-to-send (RTS) and clear-to-send (CTS) message exchange to make predictions of future traffic on the medium and updates the network allocation vector (NAV) available in stations. Communication is established when one of the wireless nodes sends a short RTS frame. The receiving station issues a CTS frame that echoes the sender's address. If the CTS frame is not received, it is assumed that a collision occurred and the RTS process starts over. Regardless of whether the virtual carrier sense routine is used or not, the MAC is required to implement a basic access procedure as follows. If a station has data to send, it waits for the channel to be idle through the use of the CSMA/CA algorithm. If the medium is sensed idle for a period greater than a DCF interframe space (DIFS), the station goes into a backoff procedure before it sends its frame. Upon the successful reception of a frame, the destination station returns an ACK frame after a Short interframe space (SIFS). The backoff window is based on a random value uniformly distributed in the interval $[CW_{min}, CW_{max}]$, where CW_{min} and CW_{max} represents the Contention Window parameters. If the medium is determined busy at any time during the backoff slot, the backoff procedure is suspended. It is resumed after the medium has been idle for the duration of the DIFS period. If an ACK is not received within an ACK timeout interval, the station assumes that either the data frame or the ACK was lost and needs to retransmit its data frame by repeating the basic access procedure.

3. Interference in the 2.4 GHz Band

The 2.4 GHz ISM band allows for primary and secondary uses. Secondary uses are unlicensed but must follow rules defined in the Federal Communications Commission Title 47 of the Code for Federal Regulations Part 15 [COM] relating to total radiated power and the use of the spread spectrum modulation schemes. Interference among the various uses is not addressed as long as the rules are followed. Thus, the major down side of the unlicensed ISM band is that frequencies must be shared and potential interference tolerated. While the spread spectrum and power rules are fairly effective in dealing with multiple users in the band, provided the radios are physically separated, the same is not true for close proximity radios. Multiple users, including self-interference of multiple users of the same application, have the effect of raising the noise floor in the band resulting in a degradation of performance. The impact of interference may be even more severe, when radios of different applications use the same band while located in close proximity.

Thus, the interference problem is characterized by a time and frequency overlap as depicted in Figure 1. In this case, a Bluetooth frequency hopping system occupying 1 MHz of the spectrum is shown to overlap with a WLAN Direct Sequence Spread Spectrum signal occupying a 22 MHz channel. Note that, the collision overlap time depends on the frequency hopping pattern and the traffic distribution of both the Bluetooth and WLAN systems.

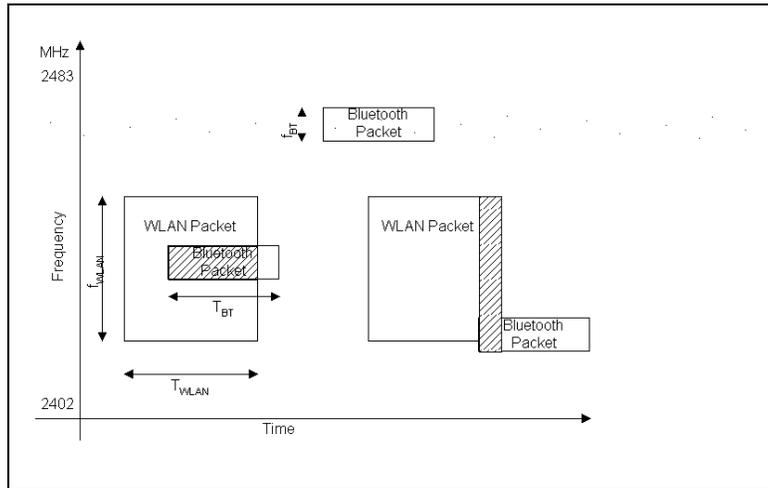


FIG. 1. *Time and Frequency Collisions in the 2.4 GHz Band*

Moreover, we can classify interferers into two classes based on their usage of the spectrum. Devices implementing the Direct Sequence Spread Spectrum (DSSS) technique constitute one class of interferer that utilize a fixed channel in the band. Typically this channel is 22 MHz wide, although the width of the signal depends on the transmitter's implementation. The second class of interferers is represented by devices implementing a type of Frequency Hopping (FH) mechanism. Note that the IEEE 802.11 specifications include a frequency hopping technique that uses a deterministic frequency pattern. On the other hand, the Bluetooth specifications define a pseudo-random frequency sequence based on the Bluetooth device address and its internal clock. While interference among systems from the same type such as Bluetooth on Bluetooth, or IEEE 802.11 on IEEE 802.11 interference can be significant, it is usually considered early on in the design stages of the protocol. Therefore, the worst realistic interference scenario consists of a mix of heterogeneous devices (i.e. devices belonging to different classes). Thus, most results published in the literature today focus on this worst case scenario.

Recently, there has been several attempts at quantifying the impact of interference on both the WLAN and the Bluetooth performance. Published results can be classified into at least three categories depending on whether they rely on analysis, simulation, or experimental measurements. Analytical results based on probability of packet collision were obtained by Shellhammer [S. 00a], Ennis [G. 98], and Zyren [J. 99] for the WLAN packet loss and by Golmie *et. al.* [N. 01b] for the Bluetooth packet error. Although, these analytical results can often give a first order approximation on the impact of interference and the performance degradation (up to 25 % for Bluetooth packet loss and close to 70% for WLAN packet loss), they often make a number of assumptions concerning the traffic distributions and the operation of the media access protocol

which can make them less realistic. More importantly, in order for the analysis to be tractable, mutual interference that can change the traffic distribution for each system is often ignored. On the other hand, experimental results such as the ones obtained by Kamerman [A. 00], Howitt *et. al* [I. 01], and Fumolari [D. 01] can be considered more accurate at the cost of being too specific to the implementation tested. Thus, a third alternative consists of using modeling and simulation to evaluate the impact of interference. This third approach can provide a more flexible framework. However, the accuracy of the results depends on the modeling assumptions made. Zurbes *et. al.* [S. 00b] present simulation results for a number of Bluetooth devices located in a single large room. They show that for 100 concurrent web sessions, performance is degraded by only five percent. Golmie *et. al.* [N. 01c] use a detailed MAC and PHY simulation framework to evaluate the impact of interference. Similar results have been obtained by Lansford *et. al.* [J. 00a] who use simulation and experimental measurements to quantify the interference resulting from Bluetooth and IEEE 802.11. Their simulation models are based on a link budget analysis and a Q function calculation for the channel and PHY models respectively, in addition to the MAC layer behavior.

4. Coexistence Framework

Wireless system designers have always had to contend with interference from both natural sources and other users of the medium. Thus, the classical wireless communication design cycle has consisted of measuring or predicting channel impairments, choosing a modulation method, signal pre-conditioning at the transmitter, and processing at the receiver to reliably construct the transmitted information. However, in contrast to classical techniques to suppress interference such as modulation, channel coding, interleaving and equalization, most of the techniques proposed for solving the problem of interference in the 2.4 GHz band focus on adaptive non signal processing control strategies including power and frequency hopping control, and MAC parameter adjustments and scheduling.

In fact, there are a number of industry led activities focused on coexistence in the 2.4 GHz band. The IEEE 802.15.2 Coexistence Task Group was formed in order to evaluate the performance of Bluetooth devices interfering with WLAN devices and develop a model for coexistence which will consist of a set of recommended practices and possibly modifications to the Bluetooth and the IEEE 802.11 standard specifications [802] that allow the proper operation of these protocols in a cooperating way. At the same time, the Bluetooth Special Interest Group (SIG) formed its own task group on Coexistence. Both the Bluetooth and the IEEE working groups maintain liaison relations and are looking at similar techniques for alleviating the impact of interference. The proposals considered by the groups range from collaborative schemes intended for Bluetooth and IEEE 802.11 protocols to be implemented in the same device to fully independent solutions that rely on interference detection and estimation.

Collaborative Mechanisms-

Mechanisms for collaborative schemes have been proposed to the IEEE 802.15 Co-

existence Task Group and are based on a MAC time domain solution that alternates the transmission of Bluetooth and WLAN packets (assuming both protocols are implemented in the same device and use a common transmitter) [J. 00b]. A priority of access is given to Bluetooth for transmitting voice packets, while WLAN is given priority for transmitting data.

Non-Collaborative Mechanisms-

The non-collaborative mechanisms considered range from adaptive frequency hopping [B. 01] to packet scheduling and traffic control [N. 01a]. They all use similar techniques for detecting the presence of other devices in the band such as measuring the bit or frame error rate, the signal strength or the signal to interference ratio (often implemented as the Received Signal Indicator Strength (RSSI)). For example, each device can maintain a bit error rate measurement per frequency used. Frequency hopping devices can then know which frequencies are occupied by other users of the band and thus modify their frequency hopping pattern. They can even choose not to transmit on a certain frequency if that frequency is occupied. The first technique is known as adaptive frequency hopping, while the second technique is known as MAC scheduling. Each technique has advantages and disadvantages. One of the advantages in using a scheduling policy is that it does not require any changes in the FCC rules. In fact, title 47, part 15 of the FCC rules on radio frequency devices [COM], allows a frequency hopping system to recognize the presence of other users within the same spectrum band so that it adapts its hopsets to avoid hopping on occupied channels. Furthermore, scheduling in the Bluetooth specifications is vendor implementation specific. Therefore, one can easily implement a scheduling policy with the currently available Bluetooth chip set. On the other hand, adaptive frequency hopping requires changes to the Bluetooth hopping pattern and therefore a new Bluetooth chip set design. While both techniques can reduce the Bluetooth packet loss and the impact of interference on the other system, only the adaptive frequency hopping technique can increase the Bluetooth throughput by maximizing the spectrum usage.

Figure 2 illustrates the coexistence mechanisms space with respect to the duty cycle or the device activity and frequency band occupancy. As the number of interferers increase, each system is forced to transmit less often in order to avoid collisions. Thus, as the band occupancy increases, the duty cycle is reduced imposing time domain solutions. Frequency domain solutions such as adaptive frequency hopping can only be effective when the band occupancy is low.

5. Factors Impacting Interference

In this section we discuss different factors that may impact interference. Our discussion is based on performance results obtained from our detailed simulation modeling tool [N. 01c]. The example scenario that we use is based on a four node topology including two WLAN nodes (1 access point (AP) and one mobile device) and two Bluetooth nodes (1 master and 1 slave). Data is transmitted from the mobile WLAN node to the AP that responds with acknowledgement messages upon the successful

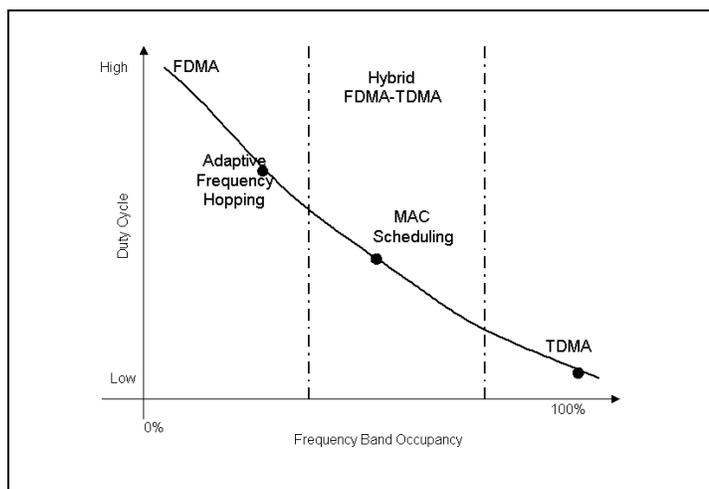


FIG. 2. *Coexistence Solution Space*

receipt of data packets. In order to better visualize the topology we can think of the placement of the four wireless devices on a two dimensional grid. The WLAN devices are located at $(0,15)$ and $(0,d)$ meters for the AP and mobile device respectively. The Bluetooth devices are placed at $(0,0)$ and $(1,0)$ meters for the slave and master device respectively. The transmitting power is set to 25 mW and 1 mW for WLAN and Bluetooth respectively. Statistics are collected at the Bluetooth slave device and the WLAN mobile node. Note that the distance between the WLAN mobile node and the Bluetooth slave is varied along the "y" coordinate axis. The WLAN traffic distribution is set as follows. The offered load is set to 50% of the channel capacity. The packet size is 8000 bits and the packet interarrival time is set to 1.86 ms. The configuration and system parameters are summarized in Table 1.

Choice of Bluetooth Voice Encapsulation-

Figure 3 illustrates the effect of choosing different packet encapsulation schemes for transmitting Bluetooth voice packets in an interference environment. The encapsulation varies from *HV1* that use a $1/3$ FEC rate and a $T_{SCO} = 2$, to *HV2* that use a $2/3$ FEC rate and a $T_{SCO} = 4$, and *HV3* that use no FEC and a $T_{SCO} = 6$. Note that there is no difference in the total packet length between the different HV packets. From Figure 3(a), we observe that the choice of packet encapsulation does not impact the performance of Bluetooth, in other words the use of additional error correction does not improve performance. On the other hand, we note from Figure 3(b) that *HV3* is "friendlier" to WLAN due to a longer T_{SCO} period.

FEC Efficiency -

We use three types of Bluetooth packet encapsulations, namely, *DM1*, *DM3*, and *DM5*, that occupy 1, 3 and 5 slots respectively. The offered load for Bluetooth is set to 30% of the channel capacity which corresponds to a packet interarrival of 2.91 ms,

Simulation Parameters	Values
Propagation delay	5 μ s/km
Length of simulation run	30 seconds
Bluetooth Parameters	Values
Transmitted Power	1 mW
Slave Coordinates	(0,0) meters
Master Coordinates	(1,0) meters
WLAN Parameters	
Packet Length	8000 bits
Packet Interarrival Time for 11 Mbits/s	1.86 ms
Transmitted Power	25 mW
AP Coordinates	(0,15) meters
Mobile Coordinates	(0,d) meters
Packet Header	224 bits
Slot Time	$2 * 10^{-5}$ seconds
SIFS Time	$1 * 10^{-5}$ seconds
DIFS Time	$5 * 10^{-5}$ seconds
CW_{min}	31
CW_{max}	1023
Fragmentation Threshold	None
RTS Threshold	None
Short Retry Limit	4
Long Retry Limit	7

TAB. 1. *Simulation Parameters*

8.75 ms and 14.58 ms for *DM1*, *DM3* and *DM5* packets respectively. In this case we note from Figure 4 that the use of FEC has limited benefits and can only improve the performance of Bluetooth for low interference scenarios (i.e. for distances greater than 3 meters).

Effect of Fragmentation on the Interfering System-

Fragmentation or the transmission of short packets is a well documented technique to alleviate the impact of interference since a shorter packet has a lower probability of collision with an interfering system. However, Figure 5 shows that fragmentation may degrade the performance of the interfering system.

6. Concluding Remarks

In this paper we focus on the problem of interference in the 2.4 GHz unlicensed band. We first define the problem and discuss some of the results previously published in the literature on the evaluation of interference. We then give an overview of

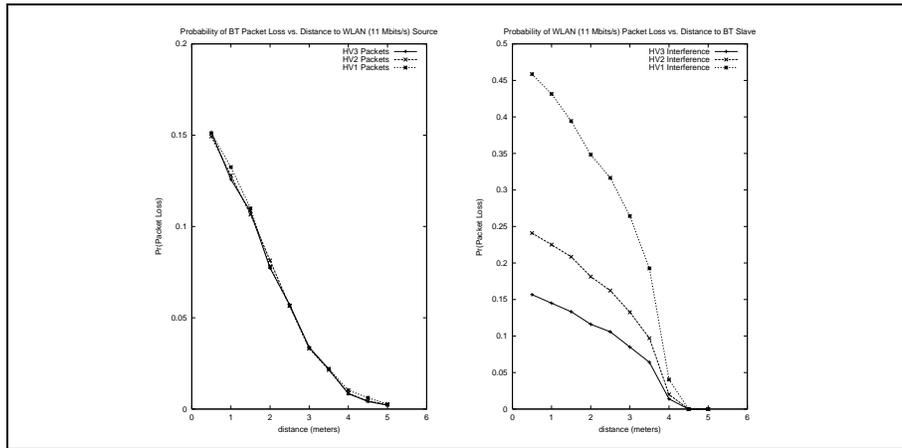


FIG. 3. (a) (b) Bluetooth voice packets with 802.11 interference. (a) Probability of BT packet loss vs. distance to WLAN Source. (b) Probability of WLAN packet loss vs. distance to BT Slave

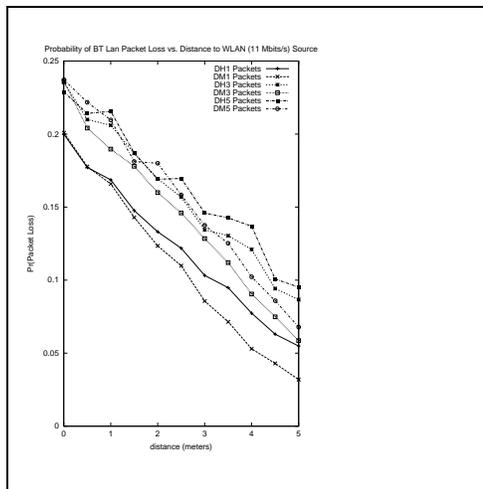


FIG. 4. Probability of BT packet loss vs. distance to WLAN source

the coexistence framework consisting of several techniques proposed to alleviate the impact of interference. Several factors that can impact the performance of Bluetooth and WLAN in an interfering environment are explored. We make several observations regarding the use of FEC, the choice of packet encapsulation and fragmentation and the effect on performance. Our results indicate that the use of FEC has limited benefit for many interfering scenarios. In addition, applying fragmentation can reduce the

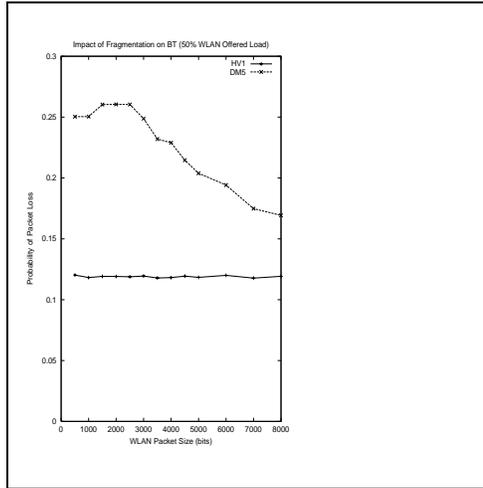


FIG. 5. *Probability of BT packet loss vs. distance to WLAN source*

probability of packet loss at the expense of causing more interference to the "other" system.

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